UNITED STATES PATENT APPLICATION

OF

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FOR

DETERMINING THE COMPOSITION OF SUBSCRIBER LOOPS

FROM FREQUENCY DOMAIN MEASUREMENTS

DETERMINING THE COMPOSITION OF SUBSCRIBER LOOPS
FROM FREQUENCY DOMAIN MEASUREMENTS

CROSS REFERENCE TO RELATED APPLICATION

This application claims the benefit of U.S. Provisional No. 60/265,411, filed February 1, 2001, the contents of which are herein incorporated by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to telephone subscriber loops and, more particularly, to methodologies and concomitant systems for determining the composition of a subscriber loop from frequency domain measurements at the input of the loop.

2. Description of the Background Art

With the deployment of high-speed data transmission techniques on subscriber telephone loops, such as ISDN (Integrated Services Digital Network) and DSL (Digital Subscriber Loop), there has been a renewed interest in devising a technique for determining the composition of the loops from so-called single-ended measurements in order to qualify such loops for such high-speed digital transmission. A telephone subscriber loop typically connects a customer with a local telephone central office and is composed of lengths of copper cable such as, for example 26 gauge or 24 gauge cable. It is especially desirable to estimate the configuration of a loop from measurements made at the end of the loop terminating at the central office. For example, one might measure the complex input impedance at the input of the loop over a range of frequencies (generally

referred to as the frequency domain or "swept-frequency approach"), or the time-domain

echo at the input to the loop (generally referred to as the time domain or "time domain

reflectometer" approach). From these measurements, the composition of the loop is

estimated using identifiable characteristics in the response, such as peaks of return

5   signals in the frequency domain or time intervals between peaks in the response signal.

Moreover, based upon estimates of the loop configuration from these measurements, it is

further possible to estimate the transmission characteristics of the loop to the customer

end. It is desirable to effect such measurements using a single-ended approach at the

central office so such tests can be automated.

10   One prior art reference that treats aspects of the loop composition problem

is U. S. Patent No. 3,904,839, dated September 9, 1975, issued to Peoples and entitled

"Loop Fault Locator". The focus of '839 is on locating cable "faults". In the past, a

successful fault location program generally involved the following steps: fault

sectionalization, fault localization, and fault pinpointing. Each step produced a more

15   refined estimate to the location of a fault. The goal of fault sectionalization is that of

locating the access point (e.g., terminal, splice, cross-connect box) nearest the fault from

measurements at the central office. The fault localization activity uses measurements at

the access point to further refine the estimate of the location of the fault. Finally, fault

pinpointing involves "walking" the loop with loop test equipment to zero in on the fault.

20   The definition of "fault" is very broad in this context. Certain loop

conditions are indeed faults, such as an open in one of the two conductors comprising a

loop, or a short at some point in the loop. On the other hand, other conditions are truly

not faults in the usual sense; for example, a gauge change (a cable of one gauge such as

26 gauge being spliced to a cable of another gauge such as 24 gauge) could be interpreted

as a fault since there is an electrical discontinuity at the junction of the two gauges (that is, the two gauges have different primary or secondary electrical constants). However, such a cascade of gauges is actually designed into the loop. The smaller gauge such as 26 gauge is purposely placed closest to the central office to reduce congestion in

5   conduits. Other, coarser gauges are used remotely from the central office to ensure the customer has sufficient current to operate the telephone or other customer premises equipment. The terminology is generalized herein so both actual faults and perturbations due to, for example, gauge changes or the end-of-loop are referred to as irregularities.

The technique of '839 uses a frequency domain approach. The input

10   impedance phase derivative is measured across a range of several octaves above a specified starting frequency to produce a corresponding periodic function. Each irregularity (such as low resistance splice or a gauge change) produces an additive sinusoidal variation in the phase derivative as frequency is increased. The frequency of each sinusoidal variation is linearly related to the distance to the corresponding

15   irregularity and, therefore, provides an estimate to the distance to the irregularity. The frequencies of the sinusoids are determined, using analog or digital means such as computer processing, from the maxima in a transformed function determined from the periodic swept-frequency function.

Numerous other loop functions are measurable at the input to the loop,

20   including the magnitude of the input impedance, the real part of the input impedance, the imaginary part of the input impedance, the phase or phase derivative of the input impedance, and functions related to the return loss (a term of art wherein the input impedance is compared to a reference impedance) such as the real part, the imaginary part, and so forth as for the input impedance alone. The '839 reference uses the phase

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Wderivative of the input impedance because, empirically, it is the most sensitive indicator of the distance to irregularities.

There are known limitations on single-ended measurements made in either the time domain or frequency domain. For example, with the swept-frequency technique of '089, if two faults are closely spaced, then the power spectral peak of one fault can dominate or mask the power spectral peak of the other fault. This problem is characterized as one of "resolution", that is, how far apart must irregularities be in order to mitigate interaction to find the associated peak of each irregularity. There is no ready answer to this; each loop must be evaluated separately due to the complexity of the interaction effects of various irregularities. Also, each irregularity gives rise to a multiplicity of sinusoidal terms that can mask even the fundamental sinusoidal frequency of another irregularity. This masking effect is not crucial if the intent is to merely "sectionalize" an irregularity. However, to qualify loops for ISDN or DSL deployment, the coarse results obtained by using the technique of '089 are typically not satisfactory.

Besides the limitations imposed by loop composition such as closely space irregularities, there is also the known problem of estimating peaks in a power spectrum which has been generated using data limited to a finite range of frequencies. This problem falls into the class of interval-limited time or frequency domain sampling. The limited amount of data is equivalent to truncating the complete frequency domain representation of the function being measured by a "weight function". The default, and typical, weight function is a rectangular window. However, such a weight function severely distorts the peaks in the power spectrum because of the interaction of the slow decay of the weight function in the power spectral domain, that is, the transform domain. Improved resolution can be achieved if another weight window is used. Known

examples of such weight windows are the raised-cosine, Hamming window, or Kaiser window. However, even with these "weight windows" there is still the possibility of distortion in the transform domain because of so-called "aliasing" wherein spectral components are interfered with by the decay (albeit more rapid than the rectangular

5 window) of these weight functions in the transform domain.

The prior art is devoid of improved signal processing techniques that can refine the resolution of the swept-frequency measurements so as to further identify previously-masked peaks in the power spectrum. Whenever more peaks can be identified, the composition of the loop can be estimated with greater accuracy.

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SUMMARY OF THE INVENTION

These shortcomings, as well as other limitations and deficiencies are obviated, in accordance with the present invention relating to the composition of a subscriber loop, by improved signal processing techniques that can refine the resolution

15 of the swept-frequency measurements so as to further identify previously-masked peaks in the power spectrum.

In accordance with a broad method aspect of the present invention, a method for estimating distances to irregularities on a subscriber loop includes: (a) measuring a loop response as a function of frequency at a loop end; (b) weighting the

20 loop response with a pre-selected prolate spheroidal wave function to produce a weighted response; and (c) generating a spectral analysis of the weighted response wherein the estimated distances to the irregularities correspond to peaks in the spectral analysis.

In accordance with another broad method aspect of the present invention, a method for estimating distances to irregularities on a subscriber loop includes: (a)

measuring the real part of the return loss of the loop using a pre-selected reference

impedance over a band of frequencies to generate a loop response; (b) weighting the loop

response with a spectral window to generate a weighted loop response; (c) iteratively

multiplying the weighted loop response with a pre-determined multiplier function to

5 produce a characteristic function; (d) transforming each iteratively produced

characteristic function to determine a set of corresponding characteristic values; and (e)

selecting local maxima from the set of characteristic values as estimates to the distances

to the irregularities. The broad system aspect of the present invention is commensurate

with this broad method aspect.

BRIEF DESCRIPITON OF THE DRAWING

10 The teachings of the present invention can be readily understood by

considering the following detailed description in conjunction with the accompanying

drawings, in which:

FIG. 1 is a frequency-domain plot of a loop response corresponding to the

15 real part of return loss for a loop of 5000 feet of 26-gauge cable terminated in a

conventional telephone set wherein the reference impedance equals to the characteristic

impedance of 26-gauge cable and the frequency ranges from 100 kHz to 600 kHz;

FIG. 2 is a transform domain or spectral domain plot of the loop response

of FIG. 1 depicting the single peak corresponding to the end of the loop using a technique

20 of the prior art;

FIG. 3 is a frequency-domain plot of a loop response corresponding to the

real part of return loss for a loop composed of 5000 feet of 26-gauge cable in cascade

with 3000 feet of 24-gauge cable feet terminated in a conventional telephone set wherein

the reference impedance equals to the characteristic impedance of 26-gauge cable and the frequency ranges from 100 kHz to 600 kHz;

FIG. 4 is a transform domain or spectral domain plot of the loop response of FIG. 3 depicting a discernible peak corresponding to the end of the loop at 8000 feet and an essentially "masked peak" corresponding to the gauge change at 5000 feet using a technique of the prior art;

FIG. 5A is a plot of the zero-order prolate spheroidal wave function in the frequency domain over the frequency range 100 kHz to 600 kHz;

FIG. 5B is a plot of the pswf in the transform domain depicting its finite support;

FIG. 5C is a plot of the rectangular window in the transform domain depicting its slow decay;

FIG. 6 is a plot of the weighted response of the loop of FIG. 1 obtained by multiplying the loop response of FIG. 3 by the wave function of FIG. 5;

*FIG. 7 is a transform domain or spectral domain plot of the loop response of FIG. 6 for comparison to FIG. 2 wherein the single peak corresponds to the end of the loop;

FIG. 8A repeats FIG. 4 for comparison to FIG. 8B which is a transform domain or spectral domain plot of the loop response of FIG. 3 weighted by the wave function of FIG. 5 to show that two peaks corresponding to the gauge change and the end of the loop are now readily identified;

FIG. 9 is a plot of the characteristic values for the weighted loop response described in FIG. 3 depicting the two spectral peaks corresponding to irregularities as a function of distance;

FIG. 10 is a transform or spectral domain plot of a loop response corresponding to the real part of return loss weighted by the wave function of FIG. 5 for a loop composed of: 10000 feet of 26-gauge cable, a bridged tap of 301 feet of 24 gauge cable, and 1000 feet of 26-gauge cable feet terminated in a conventional telephone set wherein the reference impedance equals to the characteristic impedance of 26-gauge cable and the frequency ranges from 100 kHz to 600 KHz;

FIG. 11A is a plot of the characteristic values for the weighted loop response described in FIG. 9 depicting numerous spectral peaks corresponding irregularities;

FIGS. 11B – 11H are plots of the characteristic values of candidate loops for comparison to the characteristic values of FIG. 11A;

FIG. 11I is a plot of the characteristic values for the weighted loop response described in FIG. 9 wherein the measured loop response is corrupted by a noise of $\pm 10\%$ to show the robustness of the characteristic values to noise;

FIG. 12 is a high-level block diagram of circuitry for measuring the return loss as a function of frequency; and

FIG. 13 is a flow diagram for the estimating distances to irregularities.

To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures.

DETAILED DESCRIPTION

The disclosure of U.S. Patent No. 3,904,839 is incorporated herein by reference; however, this detailed description will provide sufficient details to make this disclosure basically self-contained when pertinent to the claims.

Function Theoretical Basis

The return loss of a loop, $R(\omega)$, is defined by:

$$R = R(\omega) = \frac{Z_{in}(\omega) - Z_{ref}(\omega)}{Z_{in}(\omega) + Z_{ref}(\omega)}, \tag{1}$$

where $\qquad$ ω is the radian frequency,

$Z_{in}(\omega)$ is the input impedance of the subscriber loop as determined

from the central office end of the loop, and

$Z_{ref}(\omega)$ is a reference impedance.

There are two forms for equations (1): (i) a closed form for a simple loop

configuration; and, (ii) a summation form for a complicated loop configuration. Each

will be explained in order below.

Closed Form for a Simple Loop Configuration

In order to gain an insight of the principles in accordance with the present

invention, it is enlightening to study a simple case of equation (1) which can be derived

in closed form. Suppose that the subscriber loop under consideration is a single gauge

cable of length L that is open-circuited at the far-end for the range of frequencies of

interest (e.g., the customer's telephone instrument is on-hook), and $Z_{ref}(\omega)$ is chosen as

equal to the characteristic impedance, designated $Z_0(\omega)$, of the given cable gauge. Since

the loop is open-circuited at the far end, using well-known relations for electrical

transmission lines, $Z_{in}(\omega)$ may be expressed as

$$Z_{in}(\omega) = Z_0(\omega)\frac{ctnh(\gamma L)}{sinh(\gamma L)}$$, where $\gamma = \alpha + j\beta$ is the complex

propagation of the cable gauge as a function of frequency. Then R in equation (1) can be

reduced to $R = exp(-2\gamma L)$. Taking the real part of R yields:

$Re(R) = exp(-2\alpha L)cos(2\beta L)$.

5   It is readily apparent that for this simple loop structure that the real part of

the return loss is a co-sinusoidal waveform weighted by a decaying exponential. The

cosine has a period determined by the cable length L. Accordingly, since the real part of

return loss in the swept-frequency domain is a co-sinusoidal signal, it is possible, for

example, to process $Re(R)$ by a Fast Fourier Transform (FFT) to obtain the "spectral

10   content" of $Re(R)$ in a transformed domain. In this transformed domain, due to the co-

sinusoidal nature of $Re(R)$, the "spectral content" has one peak representative of the

periodicity of the co-sinusoid. The period of the co-sinusoid is proportional to cable

length L.

        To further demonstrate these principles graphically, reference is now

15   made to FIG. 1 initially. FIG. 1 is a frequency-domain plot of a loop response

corresponding to the real part of the return loss versus frequency for a loop of 5000 feet

of 26-gauge cable terminated in a conventional telephone set wherein the reference

impedance equals to the characteristic impedance of 26-gauge cable and the frequency

ranges from 100 kHz to 600 kHz. The exponentially damped co-sinusoidal behavior is

20   quite apparent.

        FIG. 2 is a transform domain or spectral domain plot of the loop response

of FIG. 1 depicting the single peak corresponding to the end of the loop using the default

rectangular weight window of the prior art. The plot of FIG. 2 is obtained by applying a

Fast Fourier Transform algorithm to the real part of the return loss. It is possible to estimate the distance to the irregularity (that is, the end of the loop since the cable abruptly ends in an open-circuit) using the relationships disclosed in U. S. Patent No. 3,904,829, already alluded to in the Background Section, namely equations (4) and (8) in

5   '829. However, as set forth below, a simpler and more accurate technique is elucidated. Thus, since the present interest is only in qualitative comparisons, the location of the peak at an abscissa value of approximately 170 is noted (the abscissa is a data-point normalized scale used for comparison to other plots discussed and shown below which are also normalized).

10

Summation Form for a Complicated Loop Configuration

For loops other than the simple configuration of a single length of cable, the loop response is very complex. Based on the simple case, the real part of the return loss is represented as a summation follows as:

15

$$R = R(\omega) = \sum_{i=1}^{N} \sum_{j=1}^{\infty} A_{ij}(\omega) exp(-2j\alpha_i L_i) cos(2j\beta_i L_i + \theta_i) \qquad (2)$$

where $A_{ij}(\omega)$ is an amplitude function of ω,

N is the number of irregularities,

L_i is the distance to the ith irregularity, and

α_i and β_i are the real and imaginary parts of the complex propagation

20   constant associated with the ith irregularity.

Another way to write equation (2) is as follows:

$$R(\omega) = \sum_{i=1}^{N} A_i(\omega)exp(-2\alpha_i L_i)cos(2\beta_i L_i) + \text{multiple ``reflection'' terms.} \qquad (3)$$

The manifestation of the multiple "reflection" terms will be apparent in the discussion that follows.

To demonstrate equations (2) or (3) graphically, reference is made to FIG.

5   3 which shows a frequency-domain plot of a loop response corresponding to the real part

of return loss for a loop composed of 5000 feet of 26-gauge cable in cascade with 3000

feet of 24-gauge cable feet terminated in a conventional telephone set wherein the

reference impedance equals to the characteristic impedance of 26-gauge cable and the

frequency ranges from 100 kHz to 600 kHz. The loop response is characterized by a

10   superposition of damped co-sinusoids wherein the amplitude as a function of frequency

no longer has the simple decaying exponential form exhibited in FIG. 1, and the zero

crossings are no longer uniform as the case in FIG. 1.

FIG. 4 is a transform domain or spectral domain plot of the loop response

of FIG. 3, using rectangular weight window, that depicts a discernible peak

15   corresponding to the end of the loop at 8000 feet and an essentially "masked peak"

corresponding to the gauge change at 5000 feet. The interpretation of FIG. 4 is very

difficult in the sense that if the loop configuration is not known beforehand, it is most

likely one would be unsure if there is an irregularity in the abscissa range (157,235). Yet,

given the postulated loop structure, one would also expect a peak at about 170 from the

20   example covered by

FIGS. 1 and 2. The masking of the peak corresponding to 5000 feet of 26-gauge cable is

due to the fact that the irregularity at the gauge change is not as significant as the

irregularity at the end of the loop. The irregularity at the gauge change is merely due to

the change in cable gauge, that is, transitioning between gauges with cable constants that differ moderately, as compared to an abrupt open at the end of the loop, that is, transitioning from a gauge with a finite characteristic impedance to an open-circuit. The slow decay of the rectangular window in the transform domain centered on the distance

5   representing the end of the line severely masks the peak due to the gauge transition.

To demonstrate how the results in the spectral domain can be improved significantly, a new window is introduced to reduce spectral interactions.

Prolate Spheroidal Wave Function (pswf) Window

10   A very useful window to improve the distance estimates in the spectral domain is the zero-order prolate spheroidal wave function (pswf) window. The pswf weighting basically eliminates slow decay of the weight function in the power spectral domain because the pswf has the unusual characteristic of being essentially limited in support or extent in both the frequency domain and in the transform domain. A

15   algorithm for the pswf waveform useful for computer-based analysis is shown by the FORTRAN subroutine in the sole APPENDIX.

FIG. 5A is a plot of the zero-order prolate spheroidal wave function in the frequency domain over the frequency range 100 kHz to 600 kHz, which is compatible with the abscissa of the plots of FIGS. 1 and 3.

20   FIG. 5B is a plot of the pswf waveform in the transform domain depicting its finite support.

FIG. 5C is a plot of the rectangular window in the transform domain depicting its slow decay, which gives rise to aliasing, for comparison to FIG. 5B.

FIG. 6 is a plot of the weighted response of the loop of FIG. 1 obtained by multiplying the loop response of FIG. 3 by the pswf waveform of FIG. 5.

FIG. 7 is a transform domain or spectral domain plot of the weighted loop response of FIG. 6 for comparison to FIG. 2 wherein the single peak corresponds to the end of the loop. No real new information is obtained for the simple case since aliasing is not an issue for a single peak using a rectangular window.

However, the improvement fostered by the pswf waveform is readily apparent in FIG. 8 -- FIG. 8A repeats FIG. 4 for comparison to FIG. 8B which is a transform domain or spectral domain plot of the loop response of FIG. 3 weighted by the pswf waveform. Clearly, the two peaks corresponding to the gauge change and the end of the loop are now easily identified.

Length Estimates Using the Characteristic Function and Characteristic Values

To both determine estimates of distances to irregularities and further improve the resolution in the spectral domain, additional signal processing on the pswf-weighted loop response is now introduced.

First, a so-called characteristic function for a loop response is determined based upon the following well-known relation:

$$\cos(A)\cos(B) = [\cos(A-B) + \cos(A+B)] / 2 \qquad (4)$$

where A and B are arbitrary. Whenever A=B, then equation (4) becomes

$$\cos(A)\cos(A) = [1 + \cos(2A)] / 2 . \qquad (5)$$

In the spectral domain, that is, if equation (5) is transformed, there is a peak at the 0 abscissa value from the (1/2) term, and another peak at the abscissa corresponding to the term $[\cos(2A)] / 2$.

Now consider applying this principle to the loop response by multiplying equation (4) by $cos\,(2\beta_c L_c)$ where β_c is presumed known (e.g., β for 26-gauge cable, or 24-gauge cable, or an average over the known cable gauges) and L_c is a selected length. This leads to, ignoring the multiple reflection terms for the moment:

5

$$[\sum_{i=1}^{N} A_i(\omega)exp(-2\alpha_i L_i)cos(2\beta_i L_i)]\,cos\,(2\beta_c L_c). \qquad (6)$$

If $\beta_c = \beta i$, and focusing on the cosine terms only of equation (6) as follows:

$$cos\,(2\beta_i L_i)cos\,(2\beta_c L_c) = [cos(2\beta_c(L_i - L_c)) + cos(2\beta_c(L_i + L_c))]\,/\,2\,. \qquad (7)$$

If L_c is iteratively varied over a range (say over the length of the loop or even over an intermediate length encompassing the irregularities), then at values of L_c equal to the

10   $L_i's$, the right-hand side of equation (7) becomes

$$[1 + cos\,(4\beta_c L_c)]\,/2. \qquad (8)$$

Thus, peaks in the spectral domain at each L_i can be shifted to the 0-abscissa value by the proper choice of L_c. The term at the 0-abscissa is called the characteristic value. If each characteristic value is determined for each of the iteratively selected values of L_c,

15   and all the characteristic values form a set, then the peaks in the set estimate the $L_i's$.

FIG. 9 is a plot of the characteristic values for the weighted loop response described in FIG. 3 depicting the two spectral peaks corresponding irregularities as a function of distance. The range for L_c in feet is (4500, 8500), which covers the two spectral peaks at 5000 and 8000 feet; the abscissa values of 50 and 350 give a direct

20   reading of the distances to the peaks.

Characteristic Value and PSWF Applied to a Complex Loop

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As can be anticipated from the expressions of equations (2) or (3), certain loop structures can be problematic. For instance, because the loss of 26-gauge cable is greater than the other standard gauges (19, 22, 24) manifested by the real part of the complex propagation constant (namely, α), and 26-gauge cable is nearest to the central

5 office or measurement end, irregularities beyond long lengths of 26-gauge cable can be masked. To demonstrate this effect, consider the plot of FIG. 10 which is a transform or spectral domain plot of a loop response corresponding to the real part of return loss weighted by pswf waveform for a loop composed of: 10000 feet of 26-gauge cable, a bridged tap of 301 feet of 24 gauge cable, and 1000 feet of 26-gauge cable feet

10 terminated in a conventional telephone set wherein the reference impedance equals to the characteristic impedance of 26-gauge cable and the frequency ranges from 100 kHz to 600 KHz. The large peak at an abscissa of approximately 355 corresponds to the 10000-foot length of 26 gauge cable. There is a small peak at about an abscissa 400 which is barely discernible. Given the loop structure, there are at least three peaks that should be

15 discernable, namely, at 10000 feet (the "main" section), 10301 feet (the "main" section plus the bridged tap length of 301 feet), and 11000 feet (the "main" section plus the "end" section of 1000 feet).

FIG. 11A is a plot of the set of characteristic values for the pswf-weighted loop response described in FIG. 9 depicting numerous spectral peaks corresponding to

20 irregularities and/or their multiple reflections. The initial value of L_c is 9800 feet and it is incremented by 5 feet up to a value of 11800 feet. β_c is the value exhibited by 26-gauge cable. It is readily apparent that there is a characteristic value at 10000 feet. Moreover, there is another characteristic value at 10295, which is the length of the "main" section plus the bridge tap. Also, there is a peak at 10625 which corresponds to a

multiple reflection term for the bridged tap. Also, there is a peak at 11000 feet which corresponds to the "main" section plus the "end" section. Finally, there is a peak at 11295 feet which corresponds to a multiple reflection term for the sum of the main, bridged tap, and end sections.

5   The plot of FIG. 11A illustrates a technique with significant ramifications that requires reiteration. It is possible using the characteristic function/characteristic value approach to move the vantage point along a loop to focus only on a range of distances of interest (e.g., 9800 to 11800 feet in the example of FIG. 11A), while ignoring the configuration of the loop at other distances not of immediate interest. This

10   technique results in applying a so-called "distance filter" to the loop, which may be analogized to a bandpass-filter in the frequency domain.

        The ultimate utility for the set of characteristic values is one of determining loop structure. Recall that the transform domain response of FIG. 10 exhibited basically two discernible peaks. From the set of characteristic values of FIG.

15   11A, it is clear that there at least three other discernible peaks. The technique to estimate the loop structure is as follows. A set of candidate loops which is expected to have sets of characteristic values exhibited by the measured loop is postulated. This set of candidate loops is constructed based upon the information contained in the set of characteristic values for the measured loop. For example, in FIG. 11A, it is possible to

20   deduce from the set of characteristic values that there is: (a) an irregularity at 10000 feet, (b) an irregularity at 10295 feet, (c) an irregularity or a reflection showing up as a peak at 10625 feet, (d) another irregularity or reflection peak at 11000 feet, and (e) a final irregularity or reflection at 11295 feet.

A subset of the set of candidate loops may then be constructed (the subset is meant to be exemplary of the technique to construct the set of candidate loops; the actual set of candidate loops is much larger in practice). The candidate loops exhibit response characteristics that should closely resemble the loop response. The loops are

5   composed of:

(1) in cascade, 10000 feet of 26 gauge, 300 feet of 24 gauge, and 300 feet of 26 gauge; the set of characteristic values is shown in FIG. 11B;

(2) 10000 feet of 26 gauge, 300 feet of 24 gauge, a 26 gauge bridged tap of length 300 feet, and an end-section of 700 feet of 26 gauge; the set of characteristic

10   values is shown in FIG. 11C;

(3) 10000 feet of 26 gauge, a 26 gauge bridged tap of length 300 feet, and an end-section of 700 feet of 26 gauge; the set of characteristic values is shown in FIG. 11D;

(4) 10000 feet of 26 gauge, a 26 gauge bridged tap of length 300 feet, and an end-

15   section of 850 feet of 26 gauge; the set of characteristic values is shown in FIG. 11E;

(5) 10000 feet of 26 gauge, a 26 gauge bridged tap of length 300 feet, and an end-section of 850 feet of 24 gauge; the set of characteristic values is shown in FIG. 11F;

20   (6) 10000 feet of 26 gauge, a 26 gauge bridged tap of length 300 feet, a 300 foot section of 26 gauge, a 26 gauge bridged tap of 100 feet, and an end-section of 300 feet of 24 gauge; the set of characteristic values is shown in FIG. 11G;

(7) 10000 feet of 26 gauge, a 26 gauge bridged tap of 300 feet, and an end section of 1000 feet of 26 gauge; the set of characteristic values is shown in FIG. 11G.

From the responses of FIG. 11A-11G it is possible to deduce: (i) the loop of FIG. 11B has only 3 peaks in the range between the data point range (1,340), so it is eliminated from consideration; and (ii) the loop of FIG. 11D has 6 peaks, so it too is eliminated. Consider the following table of peaks in the set of characteristic values in Table 1:

Peak	FIG. 11A	FIG. 11C	FIG. 11E	FIG. 11F	FIG. 11G	FIG. 11H
first	41	10	41	41	41	41
second	100	100	100	100	106	100
third	165	150	162	160	148	167
fourth	241	210	214	212	226	241
fifth	300	298	271	267	289	300

Table 1

A "similarity measure" between the measured loop and the candidate loops is defined to evaluate the degree of similarity between the measured loop and the candidate loops. For example, one similarity measure is based upon the least-squares measure (other measures can readily be defined, such as minimum distance, and so forth) as follows:

$$\text{Similarity Measure} = \min\{ \sum_{i=1}^{peaks} (p_{mi} - p_i)^2 \}, \tag{9}$$

where p_{mi} and p_i are the peaks in the measured loop and any of the candidate loops, respectively.

This similarity measure applied to the data of Table 1 yields the loop of FIG. 11H as the loop configuration closest to the measured loop. In fact, the loop of FIG. 11H has the same electrical distances, but the gauge of the bridged tap differs from the gauge of the measured loop. This is to be expected since it is extremely difficult to differentiate gauge changes at the end of a long section emanating from the central office up to the point of the bridged tap. On the other hand, the loop configuration has been correctly identified. Note the "closeness" of loop configuration in terms of electrical length of the loops of FIGS. 11E and 11F (end section of 850 feet rather than 1000 feet). Yet the similarity measure correctly selected the loop with essentially the same electrical lengths. It must be emphasized that the loops under consideration have a combined length of over 11000 feet, so distances of the order of 100- 300 feet are only 1%- 3% of the total loop length. In other words, the technique of using the characteristic function to obtain characteristic values and, in turn, using the characteristic values to compute a similarity measure is a very sensitive technique. Moreover, and this is a critical point for other known procedures, the technique of the present invention does not require the subtraction of two large numbers (such as the input impedance or return loss, or even a time domain reflected signal) to arrive at a small number; such procedures introduced significant error which is basically uncontrollable.

In line with this discussion, the technique of the present invention is robust in the presence of noise. Other known procedures, especially those relying upon the subtraction of two large numbers, have extreme accuracy problems in the presence of noise. To demonstrate the robustness of the characteristic function approach, the plot of

the characteristic values in FIG. 11I is for the same loop used to generate FIG. 11A, that

is, the plot of FIG. 11I shows the characteristic values for the weighted loop response

described in FIG. 9 wherein the measured loop response is corrupted by a noise of

$\pm 10\%$. There is no discernible difference between the set of characteristic values with

5   and without noise.

Measuring Return Loss

High-level circuit diagram 1200 of FIG. 12 illustrates a bridge

arrangement for measuring the return loss. $V_s(f)$ (1210) is the measurement source,

which may be a swept frequency source or a periodically swept frequency source to

10   expedite frequency domain measurements. The reference impedance is shown as

$Z_{ref}(\omega)$ (1240). The input to the loop (1230) provides $Z_{in}(\omega)$. $V_m(f)$ (1220) is

measured across the bridge legs. The real part of the return loss is the in-phase

component of $V_m(f)/V_s(f)$.

Flow Diagram

15   Flow diagram 1300 of FIG. 13 depicts the series of operational steps to

carry out one broad aspect of the present invention. As shown by processing block 1310,

a measurement of a loop response is effected as a function of frequency from a loop end.

Then, as per processing block 1320, the loop response is weighted with the pswf

waveform to produce a weighted response. Next, as per processing block 1330, the step

20   of iteratively multiplying the weighted loop response with a pre-determined multiplier

function to produce a characteristic function is effected. As then shown by processing

block 1340, the step of transforming each iteratively produced characteristic function to

determine a set of corresponding characteristic values is carried out. Next, as per

processing block 1350, the step of hypothesizing a set of loops wherein each of the loops

in the set has a set of characteristic values commensurate with the set of characteristic values of the measured loop is executed. Finally, as per processing block 1360, the step of selecting one of the loops from the set of loops based upon a comparison of each set of characteristic values of each of the loops to the set of characteristic values of the measured loop completes the process.

Although various embodiments which incorporate the teachings of the present invention have been shown and described in detail herein, those skilled in the art can readily devise many other varied embodiments that still incorporate these teachings.

APPENDIX

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```
      subroutine pswfdw(x,ndata,ntrf,dps)
     dimension x(ndata)
     double precision dnd,dz,zbase,dn,cum,pr,q,crct,h,a(30)
c
c    x data array or scratch storage
c
c    ndata no. data points
c
c    ntrf iabs(ntrf) = no. of transformation points
c
c    ntrf.lt.0 - returns data window in x
c
c    ntrf.gt.0 - returns x * data window
c
c    dps  data point spacing
c
c    spheroidal expansion coefficients n=0,a=.5,c=4*pi,1-x**2
c    20 expansion coefficients sufficient for single precision
     data ntrm,h        /20,5.08125548147497d-01/
      data a(1),a(2),a(3),a(4),a(5),a(6),a(7),a(8),a(9),a(10),
     1 a(11),a(12),a(13),a(14),a(15),a(16),a(17),a(18),a(19),
     2 a(20),a(21),a(22),a(23),a(24),a(25),a(26),a(27),a(28),
     3 a(29),a(30)/
     1 4.2904633140034d-05, 1.5672417352380d-03,
     2 1.4476509897632d-02, 5.9923940532892d-02,
     3 1.4041394473085d-01, 2.1163435697968d-01,
     4 2.2242525852102d-01, 1.7233583271499d-01,
     5 1.0252816895203d-01, 4.8315671140720d-02,
     6 1.8482388295519d-02, 5.8542015072142d-03,
     7 1.5607376779150d-03, 3.5507361197109d-04,
     8 6.9746276641509d-05, 1.1948784162527d-05,
     9 1.8011359410323d-06, 2.4073904863499d-07,
     9 2.8727486379692d-08, 3.0793023552299d-09,
     1 2.9812025862125d-10, 2.6197747176990d-11,
     2 2.0990311910903d-12, 1.5396841106693d-13,
     3 1.0378004856905d-14, 6.4468886153746d-16,
     4 3.6732920587994d-17, 1.6453834571404d-18,
     5-2.1474104369670d-19,-2.9032658209519d-19/
     nti=iabs(ntrf)
     ndi=min0(nti,ndata)
     dnd=ndi
     dz=2./dnd
     zbase=-(1.d+00+dz/2.)
     nh=(ndi+1)/2
     ndp=ndi+1
     crct=dsqrt(2.*dps/(h*dnd))
     assign 80 to ng1
     if(ntrf.lt.0) assign 90 to ng1
     do 100 n=1,nh
     dn=n
     z=zbase+dz*dn
     q=1.-z**2
```

```
          cum=a(1)
          pr=1.d+00
          j=1
       50 j=j+1
          pr=pr*q
          cum=cum+a(j)*pr
          if((pr.gt.1.e-09).and.(j.lt.ntrm)) go to 50
          cum=cum*crct
          n1=ndp-n
          go to ng1,(80,90)
       80 x(n)=x(n)*cum
          if(n.eq.n1) go to 100
          x(n1)=x(n1)*cum
          go to 100
       90 x(n)=cum
          x(n1)=cum
      100 continue
          return
          end
```

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